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ARTICLE

Quantifying and Assessing Ecosystem Service Values in China's Major Grain-Producing Regions: A Spatial-Temporal Analysis

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ABSTRACT

Agricultural intensification in China has created tensions between food security imperatives and ecosystem sustainability, necessitating a comprehensive evaluation of ecological trade-offs in major grain-producing regions. This study quantified ecosystem service values (ESV) across 13 provinces during 2008–2023 using an enhanced equivalent factor methodology integrated with the Costanza valuation framework. The spatiotemporal analysis revealed that total ESV increased by 68.4% over the study period, yet significant regional disparities emerged between production capacity and ecological functionality. High-output provinces, including Heilongjiang, Henan, and Shandong, demonstrated persistently low per-unit ESV (715.5–2492.3 CNY/hm^2), remaining 40–50% below ecological leaders such as Jiangsu (3073.0 CNY/hm^2). The research identified a paradoxical inverse relationship wherein provinces contributing most to national grain security exhibited the poorest ecological performance, with cropland ESV contribution ratios varying from 3.4% in Inner Mongolia to 29.1% in Henan. Yangtze River Basin provinces emerged as exemplars of balanced development, maintaining 6.8–7.5% annual ESV growth alongside moderate production levels. The spatially differentiated framework developed from these findings suggests targeted interventions could reduce resource consumption by 18–22% in intensive farming regions while enhancing water efficiency by 30–40% in arid zones. This research provides critical evidence for transitioning China's agricultural gov-

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ernance toward integrated ecosystem management that reconciles food production with ecological sustainability.
Keywords: Food Security; Major Grain-Producing Regions; Ecosystem Service Value; Ecological Security Rationale for Terminology Selection

1. Introduction

Ecosystems offer invaluable assets and services, alongside fostering human development at an estimated value of USD 33 trillion each year [1]. These ecosystem services include provisioning functions such as the supply of food and raw materials, regulating services like climate control and water filtration, as well as supporting services which sustain biodiversity and nutrient cycling. Notably, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services indicates that over 75% of land environments have been severely modified due to human intervention, resulting in irreversible disruption of ecosystem functions [2]. Increased global food demands have resulted in agricultural intensification with biodiversity loss as a prime consequence alongside a decrease in ecosystem services. Agricultural intensification has led to substantial ecosystem degradation, with studies documenting significant biodiversity losses and ecosystem service value declines in China's agricultural regions [3, 4]. This decline puts into peril the fragile equilibrium between sustaining food production and maintaining ecological balance.

The agricultural framework in China is illustrative of such issues since the economic expansion and demographic shifts of recent decades have converted traditional farming into active zones of industrial agriculture. Within the past twenty years, there has been a marked change in the geography of grain production in China, with the northeastern and northern plains emerging as primary centres for grain production [5].

Although such transformation has facilitated unprecedented growth in grain production, meta-analyses indicate a marked decline in ecosystem service value, which accompanies the intensification of agriculture throughout China [4]. The execution of ecological restoration initiatives like Grain-for-Green has shown promise in improving ecosystem services in certain areas [6]. However, the net effects of anthropogenic activities on productivity within farmland ecosystems continue to be multifaceted and differ significantly across regions [7].

Even with more focus on the significance of ecosystem services, research specific to the intersections of food and ecology in China's grain-producing regions remains lacking. Most scholars have prioritised individual ecosystem services or specific geographic locations as subject matter without conducting holistic evaluations of agricultural landscapes involving intricate systems. Moreover, although the equivalent factor method offered by Chinese scholars aims to contextualise ecosystem service valuation [8], its use in projecting major grain-producing regions will need to be enhanced through spatial analysis alongside production-living-ecology interrelationship considerations [9]. While new insights into crop system optimisation offer prospects for attaining green growth—both environmentally and economically [10], because China's heterogeneous agricultural regions are still lacking systematic appraisal, such evaluations are advanced.

This study examines the spatiotemporal dynamics of ecosystem service values across China's major grain-producing regions, quantifies the relationship between agricultural intensification and ecological functionality, and identifies management strategies that can simultaneously optimize grain production and ecosystem services. We hypothesize that an inverse relationship exists between grain production intensity and per-unit ecosystem service values, whereby provinces achieving the highest agricultural output exhibit systematically degraded ecological functions, reflecting fundamental trade-offs between provisioning and regulating services.

To test these hypotheses, we employ an enhanced equivalent factor approach to evaluate ecosystem service values across China's 13 major grain-producing provinces from 2008 to 2023, capturing both spatiotemporal variations. The monetized evaluation framework developed herein enables quantification of production-ecology trade-offs. It informs differentiated management strategies that reconcile food security imperatives with ecological sustainability, thereby contributing to China's dual carbon goals and agricultural transformation agenda.

2. Theoretical Foundation

2.1. Agro-Ecological Coordination Theory

Agro-ecological coordination theory emphasizes the dynamic equilibrium between agricultural production and ecosystem conservation. Early frameworks in agroecology [11] advocated for sustainable agriculture by mimicking natural ecosystem structures and functions, establishing foundational principles for integrating biodiversity conservation within productive landscapes. As global ecological crises intensified, comprehensive meta-analyses revealed that agricultural intensification constitutes a key driver of biodiversity loss and soil degradation, with profound implications for ecosystem functioning [12]. These findings necessitate ecological compensation mechanisms to rebalance production-ecology synergies while maintaining agricultural viability. Contemporary research demonstrates that properly managed agricultural ecosystems can provide multiple services beyond food production, including climate regulation, water purification, and habitat provision [13].

In the Chinese context, empirical applications have yielded valuable insights for implementing agro-ecological principles. Spatial analysis of land use patterns in Sichuan Province (2000–2015) demonstrated that payment for ecosystem services models significantly enhance farmland ecosystem functions. However, success depends critically on balancing policy interventions with local farmer incentives [14]. Recent methodological advances, particularly spatial econometric approaches, enable quantification of relationships between agricultural landscape heterogeneity and ecosystem service provision. The tools employed demonstrate that landscape heterogeneity boosts carbon storage capacity and water retention, thus confirming the hypothesis of multifunctional agriculture. Alongside conceptual development, practical application of agro-ecological integration encounters enduring difficulties balancing competing aims from localised biodiversity conservation at the field level to food security for entire regions, which requires adaptive governance tailored to specific ecological contexts and socioeconomic frameworks.

The agro-ecological coordination framework operationalizes through an enhanced equivalent factor method that integrates regional productivity parameters, including yield, intensity, and input levels, to quantify intensification-induced ecological costs. The temporal analysis spanning 2008–2023 captures policy-driven agricultural transitions, while spatial differentiation recognizes zone-specific production-ecology interactions. This methodological design enables empirical validation of the hypothesized inverse relationship between grain production intensity and ecosystem service values.

2.2. Ecosystem Service Value (ESV) Theory

The Ecosystem Service Value theory provides a monetary valuation of natural capital, which underpins Eco-logic governance. The global ESV assessment was paradigm-shifting as it transformed "natural capital accounting," estimating the ecosystem services value to be USD 33 trillion annually, redefining worldwide perceptions on nature [1]. While valuation methodologies were subsequently adopted in numerous research studies, there remained problems when establishing connections between biodiversity and human wellbeing, especially concerning scale-dependency and non-linear correlations [15]. More recent frameworks have been developed to embrace these challenges through comprehensive evaluation techniques that incorporate all aspects—beyond capital—and transcend mere monetary exchange.

Within the ESV research framework in China, practitioners have made remarkable methodological and empirical contributions over the last twenty years. Systematic reviews reveal that Chinese scholars have developed dynamic equivalent factor methods and regionally differentiated valuation systems, adapting global frameworks to local ecological and socioeconomic conditions [16]. These advances have enabled more accurate quantification of ecosystem service changes resulting from land use transitions and policy interventions. Empirical evidence demonstrates that strategic investments in natural capital, such as ecological restoration programs, generate measurable improvements in ecosystem service provision across multiple categories, including water regulation, soil conservation, and carbon sequestration [17]. However, persistent challenges remain in capturing climate-land use interactions and cultural service values within existing frameworks. The transition from static to dynamic approaches in evaluation corresponds to the growing realisation that ESV impact assessments require appropriate consideration of spatial and temporal heterogeneity as well as intricate socio-ecological interactions in order to be useful for policymaking.

The methodological framework translates ESV theory into practice by replacing global coefficients with province-specific values derived from local agricultural data, incorporating temporal variations that reflect evolving agricultural practices, and disaggregating ecosystem services into nine categories tailored to China's agricultural landscapes. This approach transforms abstract ecosystem service concepts into quantifiable metrics that establish direct linkages between land use intensity and monetary valuations.

2.3. Research Gaps and Theoretical Integration

The existing literature describes two theories that form the basis of understanding agricultural sustainability through the coordination theory of agro-ecology, explaining the dialectical interplay between food production and ecological conservation, alongside ecosystem service value theory, which crystallises the quantification of human-nature interactions. There are still important gaps, however, that limit their applicability in China's grain-producing areas. The current ESV assessments remain fixated on natural ecosystems and, in doing so, overlook entirely agriculturally-dominated landscapes, which possess intricate interrelationships and synergies between economic production and ecological services on multiple levels [18]. This sectoral bias has led to the systematic neglect of recognising agricultural, multi-functional activities in addition to undervaluing the ecological contributions of farmland beyond merely providing food.

Moreover, traditional approaches to valuation lack the ability to capture and account for the ever-changing provision of ecosystem services in swiftly evolving agricultural areas. While static equivalent factor methods create a uniform framework for assessment, they fall short in depicting the total ESV impact accumulation due to persistent land use changes, policy shifts, climate changes, and other cumulative changes over time. Some scholars are trying to resolve these issues using spatiotemporal analysis techniques, which reveal the intricate relationships and the interplay of forces behind ecosystem service values at different scales [19]. Nonetheless, the integration of innovative methods into theoretical frameworks continues to be problematic in regions marked by intensive agricultural transformations. This study addresses this gap through the synthesis of ESV valuation frameworks with enhanced equivalent factor methodologies tailored for China's 13 major grain-producing regions. The integrated approach allows for a thorough assessment of agricultural ecosystem services within the context of regional heterogeneity and the spatio-temporal dynamics characteristic of these vital food production areas.

The integrated framework employs agro-ecological coordination theory to conceptualize production-conservation relationships. In contrast, ESV theory provides the valuation methodology, enabling mechanistic analysis of how agricultural intensification drives spatiotemporal ecosystem service changes.

3. Theoretical Models for Ecosystem Service Value (ESV) Assessment

The quantification and evaluation of Ecosystem Service Value (ESV) form the cornerstone for rational and efficient allocation of ecological resources. In the late 20th century, Costanza et al. pioneered global ESV assessment by categorizing ecosystem services into 17 functional types and ecosystems into 16 biomes [1], establishing the foundational valuation model [Equation (1)]:

$$V = \sum_{i=1}^{17} \sum_{j=1}^{16} A_j P_{ij} \quad i = (1, \ldots, 17), j = (1, \ldots, 16) \tag{1}$$

where:

- V : Total ecosystem service value of the study area
- A_j: Area of the *j*-th ecosystem type
- P_{ij}: Market-equivalent unit value of the *i*-th service provided by the *j*-th ecosystem

Modern approaches to valuation consider that ecosystem services arise from intricate spatial interactions and processes that depend on both scale and level, requiring methodological adaptation about the socio-economic framework and ecological properties of the region [20].

This model may have achieved global applicability, but its direct application in regional assessments overlooks systematic biases arising from spatial heterogeneity in the region's ecosystem structures as well as the mechanisms for delivering ecosystem services. Empirical studies have shown that there are critical issues with applying global coefficients at a local scale, most notably the temporal invariance assumption in highly dynamic agricultural landscapes [21]. Acknowledging these methodological limitations, delineated valuation systems based on specific areas emerged as one of the most innovative developments in ecosystem service evaluation. The Chinese approach adapted global classifications to reflect local ecological realities, creating nine functional categories which included atmospheric regulation, climatic moderation, hydrological conservation, soil formation and retention, waste assimilation, biodiversity conservation, and provisioning of food and raw materials. This refined taxonomy integrates theoretical models with practical action while addressing the core intricate relationships within agricultural mosaics.

The equivalent factor approach creates a uniform valuation methodology by setting one ESV unit to be one-seventh of the derived economic value of an average yielding cropland hectare. This method allows for consistency in normalising diverse ecosystem services across different geographical regions, as well as monetarily systematising them to enable comparison relative to each other. The value of other services was adjusted according to the proportions obtained from the Chinese Ecosystem Service Value Equivalent Factor Table using primary or proxy ecosystem service valuation methods. This approach enables localized ESV calculations through Equation (2):

$$E_a = \frac{1}{7}\sum_{i=1}^{n}\frac{m_i p_i q_i}{M} \quad i = (1, \ldots, n) \tag{2}$$

where:

- E_a : Economic value of food production services per unit cultivated land ecosystem (equivalent ecosystem service value) (CNY/hm^2);
- i : Grain crop type
- p_i : National average annual price per unit for crop i (CNY/ton);
- q_i : Average yield per unit cultivated area for crop i (ton/hm^2);
- m_i : Sown area of crop i in the major grain-producing regions (hm^2);
- M : Total sown area of all grain crops in the major grain-producing regions (hm^2).

Calibration of parameters for agricultural productivity in China's differing agroecological zones must consider substantial heterogeneity. Current analyses of grain production dispel a spatial integration of yield potential and management intensity, which necessitates regional coefficient modification [22]. These improvements to the method ensure the precision of biophysical and socioeconomic valuations under different conditions.

The enhanced equivalent factor method, while methodologically advanced, assumes linear and additive relationships between land use and service provision, potentially overlooking ecological thresholds and synergistic effects. This study partially addresses these limitations through temporally dynamic coefficients and regional differentiation, capturing non-linear responses across discrete periods and spatial variations.

The total ecosystem service value (ESV) was calculated by summing up all ecosystem types within each study region using the products of ecosystems' spatial extents and their unit-area value coefficients. The calculation formula is expressed as Equation (3):

$$ESV = \sum (A_k \times VC_k) \tag{3}$$

- ESV : Total ecosystem service value of the study region (CNY/year).
- A_k : Spatial extent (area) of the *k*-th ecosystem type within the study region (hm^2).

- VC_k : Ecosystem service value coefficient for the k-th ecosystem type, representing the monetary value per unit area per year.

Sensitivity analysis using Monte Carlo simulations (±20% parameter perturbation) indicates ESV estimates exhibit moderate sensitivity to price variations (CV: 12–15%) and higher sensitivity to yield changes (CV: 18–22%). Provincial ESV estimates maintain uncertainty ranges of ±15–18%, with aggregate regional assessments achieving ±10–12% precision through spatial averaging.

The progression of methods in ESV assessment corresponds with the integrated socio-ecological systems shifts. Effective detection of ecosystem changes and long-term monitoring have proven that both gradual and sudden threshold responses must be aligned to a balance between ecological processes, data availability, and policy-planning timelines [23].

4. Estimation of Ecosystem Service Value Coefficients in Major Grain-Producing Regions

This research uses the years 2008, 2013, 2018, and 2023 for ESV calculations, which correspond to five-year intervals. This balances ecological process detection with data availability and policy assessment calendar windows. This temporal resolution simultaneously captures the significant transitions of the ecosystem and aligns well with statistical reporting systems in China and the country's Five-Year Plans.

Grain production information at the provincial level, including yields and cultivated areas for rice, wheat, and maize, was retrieved from the China Statistical Yearbook. Verification of commodity prices was performed through various sources such as China Grain Network and provincial agricultural trading platforms. Additionally, price inflation was handled using the Consumer Price Index for temporal alignment. Ensuring data quality involved cross-validating with regional statistical offices and identifying outliers based on standardised residuals; confirmed expert-verified anomalous values (< 2% of observations). Following the methodological framework specified in Equation (2), ecosystem service value coefficients were computed for each provincial unit, incorporating region-specific agricultural productivity parameters. The resultant spatiotemporal analysis (**Table 1** and **Figure 1**) reveals pronounced heterogeneity in ecosystem service provisioning across China's grain production landscape, with coefficients varying by factors of 2–5 between regions and exhibiting distinct temporal trajectories that reflect differential impacts of agricultural intensification and policy interventions.

Based on China's Ecosystem Service Value Equivalent Factor Table, we calculated the ecosystem service value coefficients across different functional categories for each region and year within the core grain production areas. Due to space constraints, this paper presents selected computational results, with Henan Province serving as a representative case study (**Tables 2–5**).

Table 1. Equivalent ecosystem service value coefficients in major grain-producing regions (CNY/hm^2).

Region	2008	2013	2018	2023
Hebei	957.5	1,614.5	1,549.1	2,098.2
Inner Mongolia	626.4	1,360.7	1,210.6	1,490.9
Liaoning	1,213.4	2,232.3	1,758.7	1,877.2
Jilin	1,276.2	2,387.6	1,801.4	2,060.3
Heilongjiang	715.5	1,694.9	1,497.3	1,780.9
Jiangsu	1,447.0	2,197.1	2,286.0	3,073.0
Anhui	1,088.0	1,655.3	1,814.3	2,468.3
Jiangxi	1,418.4	2,169.2	2,185.8	2,387.1
Shandong	1,275.5	1,896.6	1,831.7	2,549.4
Henan	1,219.8	1,777.8	1,824.0	2,492.3
Hubei	1,382.3	2,078.9	2,019.0	2,606.8
Hunan	1,552.0	2,191.8	2,296.0	2,430.4
Sichuan	984.7	1,544.3	1,499.6	1,893.6

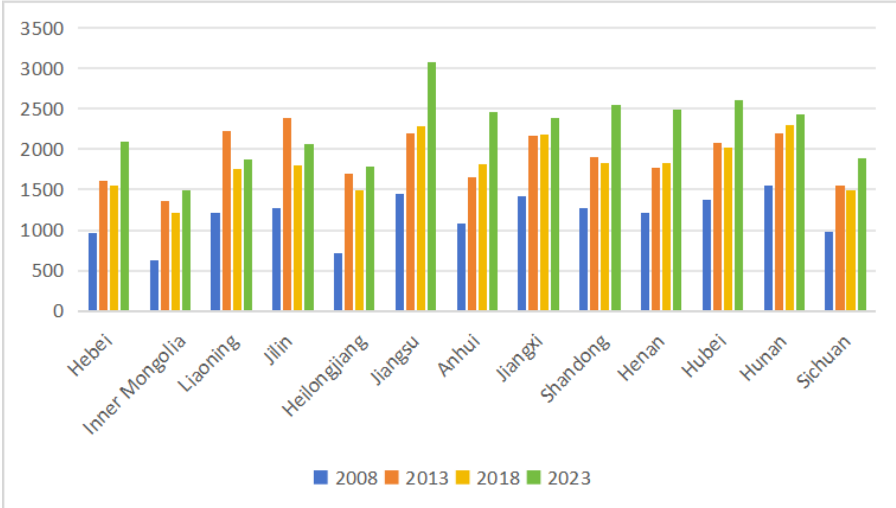

Figure 1. Equivalent coefficients of ecosystem service values in primary grain production regions.

Table 2. Ecosystem service value coefficients by functional category in Henan province (2023) (Unit: CNY/hm^2).

Ecosystem Service Function	Forest	Grassland	Cropland	Wetland	Waterbody	Desert
Gas Regulation	8,723.1	1,993.9	1,246.2	4,486.2	0.0	0.0
Climate Regulation	6,729.3	2,243.1	2,218.2	42,618.8	1,146.5	0.0
Water Conservation	7,975.4	1,993.9	1,495.4	38,631.1	50,793.6	74.8
Soil Retention	9,720.1	4,860.0	3,638.8	4,261.9	24.9	49.8
Waste Treatment	3,264.9	3,264.9	4,087.4	45,310.5	45,310.5	24.9
Biodiversity Maintenance	8,125.0	2,716.6	1,769.6	6,230.8	6,205.9	847.4
Food Production	249.2	747.7	2,492.3	747.7	249.2	24.9
Raw Material Supply	6,480.1	124.6	249.2	174.5	24.9	0.0
Cultural & Recreational Value	3,190.2	99.7	24.9	1,3832.4	10,816.7	24.9

Table 3. Ecosystem service value coefficients by functional category in Henan province (2018) (Unit: CNY/hm^2).

Ecosystem Service Function	Forest	Grassland	Cropland	Wetland	Waterbody	Desert
Gas Regulation	6,383.9	1,459.2	912.0	3,283.2	0.0	0.0
Climate Regulation	4,924.7	1,641.6	1,623.3	31,190.1	839.0	0.0
Water Conservation	5,836.7	1,459.2	1,094.4	28,271.7	37,172.7	54.7
Soil Retention	7,113.5	3,556.8	2,663.0	3,119.0	18.2	36.5
Waste Treatment	2,389.4	2,389.4	2,991.3	33,160.0	33,160.0	18.2
Biodiversity Maintenance	5,946.2	1,988.1	1,295.0	4,560.0	4,541.7	620.2
Food Production	182.4	547.2	1,824.0	547.2	182.4	18.2
Raw Material Supply	4,742.4	91.2	182.4	127.7	18.2	0.0
Cultural & Recreational Value	2,334.7	73.0	18.2	10,123.1	7,916.1	18.2

Table 4. Ecosystem service value coefficients by functional category in Henan province (2013) (Unit: CNY/hm^2).

Ecosystem Service Function	Forest	Grassland	Cropland	Wetland	Waterbody	Desert
Gas Regulation	6,222.2	1,422.2	888.9	3,200.0	0.0	0.0
Climate Regulation	4,800.0	1,600.0	1,582.2	30,399.8	817.8	0.0
Water Conservation	5,688.8	1,422.2	1,066.7	27,555.4	36,230.8	53.3
Soil Retention	6,933.3	3,466.6	2,595.5	3,040.0	17.8	35.6
Waste Treatment	2,328.9	2,328.9	2,915.5	32,319.8	32,319.8	17.8
Biodiversity Maintenance	5,795.5	1,937.8	1,262.2	4,444.4	4,426.6	604.4
Food Production	177.8	533.3	1,777.8	533.3	177.8	17.8
Raw Material Supply	4,622.2	88.9	177.8	124.4	17.8	0.0
Cultural & Recreational Value	2,275.5	71.1	17.8	9,866.6	7715.5	17.8

Table 5. Ecosystem service value coefficients by functional category in Henan province (2008) (Unit: CNY/hm^2).

Ecosystem Service Function	Forest	Grassland	Cropland	Wetland	Waterbody	Desert
Gas Regulation	4,269.3	975.8	609.9	2,195.7	0.0	0.0
Climate Regulation	3,293.5	1,097.8	1,085.6	20,858.7	561.1	0.0
Water Conservation	3,903.4	975.8	731.9	18,907.0	24,859.6	36.6
Soil Retention	4,757.2	2,378.6	1,780.9	2,085.9	12.2	24.4
Waste Treatment	1,597.9	1,597.9	2,000.5	22,176.1	22,176.1	12.2
Biodiversity Maintenance	3,976.6	1,329.6	866.1	3,049.5	3,037.3	414.7
Food Production	122.0	365.9	1,219.8	365.9	122.0	12.2
Raw Material Supply	3,171.5	61.0	122.0	85.4	12.2	0.0
Cultural & Recreational Value	1,561.4	48.8	12.2	6,769.9	5,294.0	12.2

Based on the calculated coefficients and Equation (3), we systematically quantified ecosystem service values (ESV) across subregions within China's core grain production areas. These regions are fundamentally characterized by their agricultural specialization, where croplands dominate land use (> 40% coverage), supported by three critical auxiliary ecosystems: grasslands functioning as agroecological buffers (e.g., shelterbelts), forests serving ecological conservation roles, and wetlands maintaining agricultural infrastructure (e.g., irrigation networks). While water bodies demonstrate essential hydrological functions through flood mitigation and water supply, their limited spatial presence (< 5% coverage) and indirect agricultural relevance justify exclusion from the core analytical framework. Desert ecosystems, exhibiting negligible distribution (< 0.1%), were similarly omitted. This focused approach, prioritizing cropland-forest-grassland-wetland interactions, ensures methodological rigor while preserving the analytical integrity of ESV assessments in agricultural landscapes. The resultant computations, detailed in **Table 6**, encompass three key metrics: cropland-specific ESV, total regional ESV, and the proportional contribution of cropland ecosystems to overall service value—critical indicators for evaluating ecological-economic synergies in intensive farming systems.

The results reveal substantial spatial heterogeneity in ESV distribution, with Sichuan, Inner Mongolia, and Heilongjiang maintaining the highest total ESV throughout the study period, while Henan and Shandong exhibited the highest cropland contribution ratios (> 20%), indicating intensive agricultural utilization.

Temporal analysis (**Figure 2**) demonstrates consistent ESV growth across all regions, with an average increase of 68.4% from 2008 to 2023. However, cropland contribution ratios (**Figure 3**) remained relatively stable, suggesting that ESV gains primarily originated from non-agricultural ecosystems, highlighting the importance of integrated landscape management.

Table 6. Regional ecosystem service values in core grain production regions (unit: 10 million CNY).

Region	2008			2013		
	Cropland ESV	Total ESV	Cropland ESV Contribution Ratio (%)	Cropland ESV	Total ESV	Cropland ESV Contribution Ratio (%)
Hebei	4,179.9	30,529.8	13.7%	7,308.8	51,478.1	14.2%
Inner Mongolia	3,093.7	91,950.6	3.4%	8,649.2	199,731.3	4.3%
Liaoning	3,425.5	35,790.7	9.6%	7,696.8	65,843.2	11.7%
Jilin	4,880.8	47,732.6	10.2%	11,559.8	89,301.8	12.9%
Heilongjiang	5,848.8	66,517.1	8.8%	18,579.2	157,567.9	11.8%
Jiangsu	4,763.1	35,028.7	13.6%	6,955.9	53,188.7	13.1%
Anhui	4,308.1	22,016.2	19.6%	6,729.2	33,495.0	20.1%
Jiangxi	2,771.0	44,688.8	6.2%	4,627.6	68,341.4	6.8%
Shandong	6,623.9	33,572.3	19.7%	10,004.3	49,920.0	20.0%
Henan	6,681.0	24,442.7	27.3%	10,000.3	35,623.2	28.1%
Hubei	4,455.2	39,908.8	11.2%	7,587.6	60,019.7	12.6%
Hunan	4,063.9	56,379.0	7.2%	6,284.6	79,620.1	7.9%
Sichuan	4,046.7	154,561.8	2.6%	7,186.8	242,403.8	3.0%

Table 6. *Cont.*

Region	2018			2023		
	Cropland ESV	Total ESV	Cropland ESV Contribution Ratio (%)	Cropland ESV	Total ESV	Cropland ESV Contribution Ratio (%)
Hebei	6,978.0	49,391.6	14.1%	9,309.6	67,727.4	13.7%
Inner Mongolia	9,278.4	182,500.3	5.1%	10,886.4	275,896.3	3.9%
Liaoning	5,942.5	51,871.7	11.5%	6,239.4	59,205.1	10.5%
Jilin	8,750.8	67,375.8	13.0%	10,012.6	79,019.8	12.7%
Heilongjiang	16,482.0	139,202.9	11.8%	19,584.9	182,062.3	10.8%
Jiangsu	7,297.7	55,338.7	13.2%	9,729.6	55,006.1	17.7%
Anhui	7,371.5	36,711.4	20.1%	9,950.4	47,023.0	21.2%
Jiangxi	4,788.0	68,864.7	7.0%	5,184.2	73,980.4	7.0%
Shandong	9,758.4	48,209.7	20.2%	13,556.0	60,304.4	22.5%
Henan	10,083.0	36,549.3	27.6%	13,641.5	46,849.2	29.1%
Hubei	6,989.6	58,288.9	12.0%	8,983.0	69,945.9	12.8%
Hunan	6,806.2	83,403.2	8.2%	7,159.2	85,754.9	8.3%
Sichuan	7,015.0	235,379.1	3.0%	8,823.0	322,914.1	2.7%

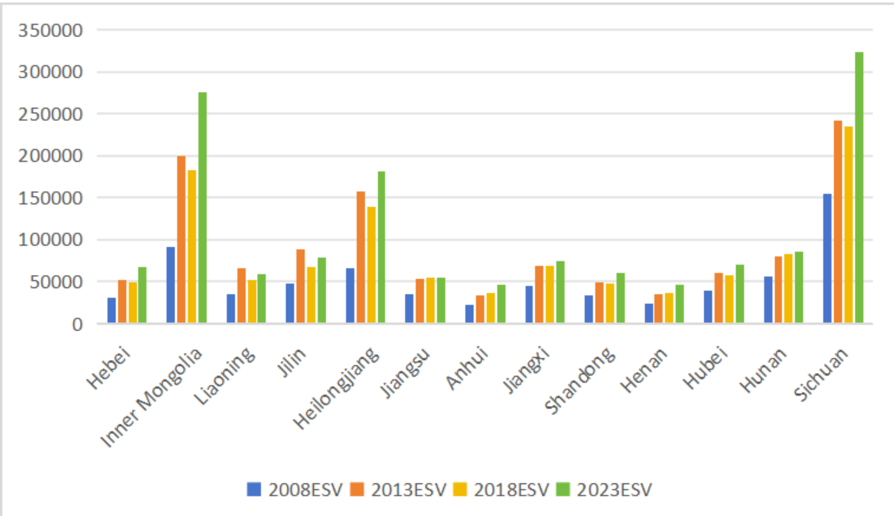

Figure 2. Total ecosystem service values by region in core grain production areas (unit: 10 million CNY).

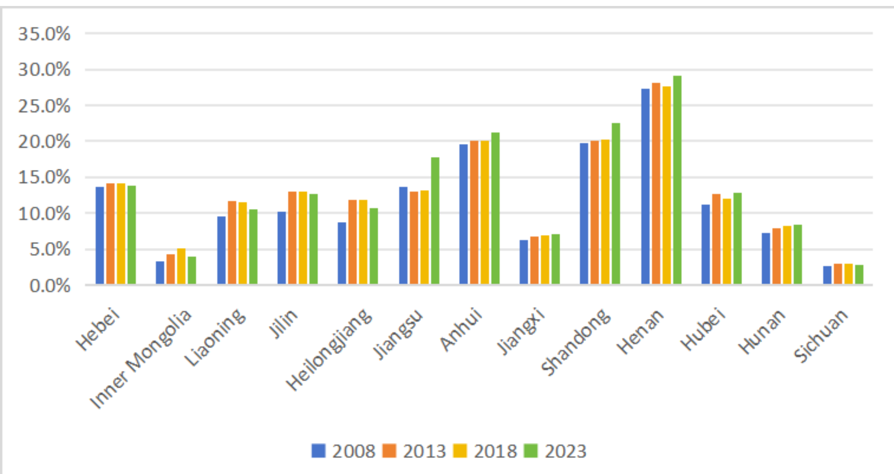

Figure 3. Regional variations in cropland ESV contribution ratios across core grain production regions.

5. Analysis of Ecosystem Service Values in Core Grain Production Regions

5.1. Equivalent Ecosystem Service Value Assessment

The spatiotemporal analysis of equivalent ecosystem service values (ESV) across China's major grain-producing regions reveals pronounced heterogeneity and a paradoxical relationship between production volume and ecological functionality. During the baseline period (2008), significant regional disparities emerged, with Yangtze River Basin provinces demonstrating superior agro-provisioning values—notably Hunan (1,552.0 CNY/hm^2), Jiangsu (1,447.0 CNY/hm^2), and Jiangxi (1,418.4 CNY/hm^2). Conversely, northern provinces exhibited markedly lower values, with Inner Mongolia (626.4 CNY/hm^2) and Heilongjiang (715.5 CNY/hm^2) recording ESV levels 54.2–59.6% below the regional mean, despite their substantial contributions to national grain production. This spatial pattern aligns with global findings that agricultural intensification often leads to ecosystem service trade-offs [24].

The study period witnessed dynamic spatial restructuring of ESV patterns. Between 2008 and 2013, most provinces experienced significant value appreciation, with Jilin achieving the most dramatic increase (87.1% to 2,387.6 CNY/hm^2). This growth momentum continued through 2023, when Jiangsu emerged as the leading province (3,073.0 CNY/hm^2), followed by Hubei (2,606.8 CNY/hm^2) and Shandong (2,549.4 CNY/hm^2). However, persistent regional disparities remained evident, as Inner Mongolia and Heilongjiang maintained values 48.5–58.0% below maximum levels throughout the entire study period.

As illustrated in **Figure 4**, the analysis reveals a striking inverse relationship between grain production volume and per-unit ecosystem service values. Heilongjiang Province exemplifies this paradox most dramatically—while achieving the highest grain output (38,873 × 10^4 tons), its ESV remained consistently below 1,800 CNY/hm^2 across all survey years. Similarly, Henan (27,067 × 10^4 tons) and Shandong (34,095 × 10^4 tons) ranked among the top grain producers yet maintained moderate ESV levels. This production-ecology decoupling suggests that high grain output has been achieved primarily through extensive cultivation and ecosystem conversion rather than ecological efficiency enhancement.

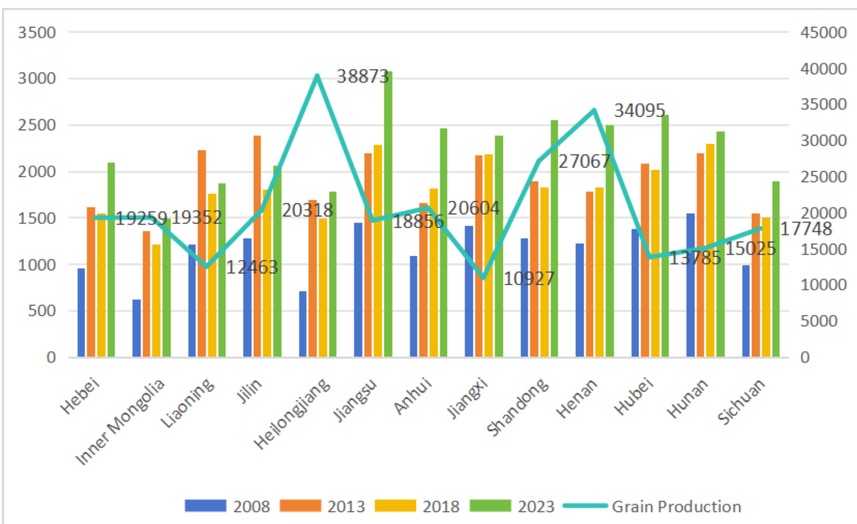

Figure 4. Comparison of equivalent ecosystem service value and total grain production across subregions in major grain-producing regions.

Temporal dynamics exhibited complex patterns across different regional clusters. The provinces located in the Yangtze River Basin, which include Jiangsu, Hunan, Hubei, Jiangxi, and Anhui, displayed steady ESV growth over the 2008–2023 period along with annual increases between 6.8% and 7.5%. These provinces sustained this growth even with relatively modest grain production amounts of 10,327–20,604 × 10^4 tons, which suggests that ecological frameworks are increasingly being embraced within the agricultural sector. In sharp contrast to these trends, southern major grain-producing provinces exhibited volatile ESV trends where Liaoning and Jilin had rapid growth from 2008–2013, followed by declines from 2013–2018 before recovering post-2020. Inner Mongolia's persistently low ESV values below 1,500 CNY/hm^2, coupled with minimal grain output of 12,163 × 10^4 tons, showcase severe ecological constraints along with poor land productivity, indicating a great deal of economic inefficiency within this region. This form of production-ecology spatial decoupling has been documented in other regions dominated by intensive agriculture, such as the US Midwest and European farming regions. These results illustrate the growing challenge for all regions to devise differentiated strategic approaches that sit somewhere between grain production and ecosystem service preservation, balancing policies tailored to specific contexts.

5.2. Analysis of Ecosystem Service Value and Cropland Contribution Rates in Major Grain-Producing Regions

The ecosystem service values (ESV) pertaining to China's prominent grain-producing regions from 2008 to 2023 highlight a persistent increase with significant spatial variation. During this timeframe, Sichuan, Inner Mongolia, and Heilongjiang have maintained dominance in ranking total ESVs, which illustrates remarkable consistency in the distribution of regional ecosystem capital. This enduring structure is paradoxical; while these high-ESV areas have claimed three of the highest ranks for food production services value, their cultivated ecosystems yielded the lowest per-acre food production service values, indicating inefficient returns relative to expansive land resources in agricultural ecosystem services.

Table 7 demonstrates the time stability of ESV rankings for provinces over the four survey years. Sichuan, Inner Mongolia, and Heilongjiang continued to occupy the top tier as Henan and Anhui interchanged in the lowest positions. The middle-ranking provinces were more volatile: prominent changes occurred between survey periods—Jilin and Hunan swapped their fourth and fifth place standing between 2008 and 2013, and then Jiangsu greatly declined from ranking eighth in 2008 to eleventh by 2023. These changes in rank highlight various regional adaptation strategies shaped by agricultural policy frameworks alongside ecosystem management interventions.

The observed decrease in total ESV with an increase in cropland contribution rates reveals underlying deficiencies within the regional agricultural systems. During the entire period of study, the provinces with the highest total ESV: Sichuan, Inner Mongolia, and Heilongjiang, exhibited cropland contribution rates that remained below ten percent. Moreover, Inner Mongolia displayed particularly troubling levels of 3.4% to 5.1%, even with expansion in agricultural activities. This indicates a lack of effective utilisation of agricultural productivity in these areas rich in natural capital. On the other hand, provinces such as Henan and Anhui, which ranked lowest in total ESV, exhibited cropland contribution rates above 20% suggesting that these regions' poor ecosystem resources have been overused and maximally exploited towards agricultural production.

The distinct development pathways are illustrated through the regional ESV growth trajectories. Jiangsu's position is declining in ranking, but alongside Anhui, Jiangxi, Henan, and Hunan, it demonstrated steady ESV growth, which indicates successful ecosystem management integration within agricultural landscapes. On the other hand, Liaoning and Jilin provinces exhibited violent oscillations, which showcase the instability of the agrarian-ecological relationship. The middle-tier provinces, such as Hubei, Jiangxi, and Hunan, showed some moderate stability in both ranks and growth trends, which may signal a balanced, sustainable level of ecosystem service provision.

Such observations highlight the multifaceted challenges of attaining sustainable agricultural development in different regions. "High-ESV" region areas with inefficient land use and "low-ESV" provinces facing ecological saturation both require starkly different policies. High-ranking provinces require strategies that enhance the agricultural utilization of existing ecosystem capital without compromising total ESV, while low-ranking provinces need ecological restoration and protection measures to rebuild depleted ecosystem functions. The observed ranking stability over fifteen years suggests that without targeted interventions, these regional disparities will persist, potentially undermining national food security and ecological sustainability objectives.

Table 7. ESV ranking of major grain-producing regions (2008–2023).

ESV Ranking	2008	2013	2018	2023
High	Sichuan	Sichuan	Sichuan	Sichuan
	Inner Mongolia	Inner Mongolia	Inner Mongolia	Inner Mongolia
	Heilongjiang	Heilongjiang	Heilongjiang	Heilongjiang
	Hunan	Jilin	Hunan	Hunan
	Jilin	Hunan	Jiangxi	Jilin
	Jiangxi	Jiangxi	Jilin	Jiangxi
	Hubei	Liaoning	Hubei	Hubei
	Liaoning	Hubei	Jiangsu	Hebei
	Jiangsu	Jiangsu	Liaoning	Shandong
	Shandong	Hebei	Hebei	Liaoning
	Hebei	Shandong	Shandong	Jiangsu
	Henan	Henan	Anhui	Anhui
Low	Anhui	Anhui	Henan	Henan

6. Strategic Recommendations for Enhancing Agricultural Ecological Efficiency

The proposed framework integrates theoretical advances in agricultural ecosystem services [13] with recent empirical findings on China's grain production patterns [9]. Building on the production-ecology decoupling and regional disparities identified in Sections 5.1 and 5.2, this study develops spatially differentiated strategies that address contemporary challenges in sustainable intensification. The framework aligns with national biodiversity conservation goals [24] while recognizing the imperative to enhance farmers' economic returns through sustainable practices. The recommendations encompass four principal production zones, each requiring interventions tailored to their specific ecological endowments and socioeconomic constraints.

6.1. Huang-Huai-Hai Plain Region (Hebei, Henan, Shandong)

This traditional grain belt, burdened by high population density (580 persons/km^2), limited arable land per capita (0.08 hm^2), and severe environmental degradation, necessitates an urgent transition to ecological intensification. Recent evidence demonstrates that agricultural productive services can significantly enhance farmers' grain profits while improving sustainability [25]. Core strategies should prioritize strict enforcement of dual conservation redlines: maintaining minimum ecological protection zones (≥ 35% territorial coverage) while preserving critical farmland (1.24 million km^2 national baseline). Infrastructure modernization must integrate precision irrigation systems and organic fertilizer networks, complemented by provincial cross-compensation mechanisms for transboundary pollution control. The implementation of circular agricultural models, combined with optimized cover crop practices [26], could reduce non-renewable resource consumption by an estimated 18–22%, addressing chronic issues of soil erosion and groundwater depletion. Based on the identified ESV gaps and resource efficiency potentials, implementation proceeds through a phased three-year approach beginning with ecosystem monitoring network establishment and precision agriculture pilots (2024–2025), followed by expanded coverage incorporating tiered ecological payments of 300–500 CNY/mu (2026–2027), culminating in mandatory sustainability certification with 25% nitrogen reduction targets (2028).

6.2. Northeast China Region (Liaoning, Jilin, Heilongjiang)

Despite abundant ecological capital, this region faces intensifying pressures from monoculture expansion. Long-term research confirms that conservation agriculture approaches can improve soil health and sustain crop yields even under warming conditions [27]. Heilongjiang requires optimized crop rotation systems balancing productivity targets (8.5 t/hm^2) with wetland conservation (≥ 23% natural wetland retention). Jilin and Liaoning should adopt integrated land-use plans sustaining forest coverage (≥ 30%) while enhancing farmland ecological functions through black soil protection engineering (annual erosion control ≤ 12 t/hm^2). Development of sustainability indices linking grain output to ecosystem service value (ESV) metrics could institutionalize ecological accountability in agricultural decision-making. Operationalization requires establishing GPS-monitored black soil protection zones, implementing differentiated subsidies linked to soil health indicators (organic matter > 3.5%), and conducting annual satellite-based compliance audits against erosion targets (< 12 t/ha/year).

6.3. Yangtze River Basin Region (Hunan, Sichuan, Hubei, Jiangsu, Jiangxi, Anhui)

Leveraging superior ecological conditions (average ESV 2,850 USD/ha), this zone should pioneer synergistic production-conservation models. Research demonstrates that agricultural diversification in such regions promotes multiple ecosystem services without compromising yield [28]. Jiangsu, Jiangxi, and Hunan can expand ecological grain production bases under the "South-North Grain Transfer" framework, integrated with cross-regional ESV accounting systems that align with national biodiversity conservation strategies and global frameworks [29]. Anhui requires focused rehabilitation of degraded farmland, aiming for a 15% increase in productivity through terrace optimization and biochar amendments. Regional development should emphasize multifunctional landscapes combining rice-fish systems with cultural ecosystem services, capitalizing on high ecological potential while meeting national food security commitments. Implementation involves establishing trans-provincial ESV trading platforms (50–80 CNY/unit) by 2025, deploying IoT-satellite monitoring systems for transparent accounting, and creating demonstration zones documenting 20–30% income premiums from ecological intensification.

6.4. Inner Mongolia Region

Addressing water scarcity (annual precipitation ≤ 400 mm) and ecological fragility demands innovative dryland strategies. This region exemplifies the challenges where land-use change threatens progress toward sustainable intensification [30]. Marginal farmland retirement programs (targeting 8% conversion to grassland/forest) should be coupled with water-rights trading systems, ensuring ecological baseflows (≥ 25% river maintenance). Adoption of drought-resistant crop varieties and photovoltaic-agriculture integration could enhance water use efficiency by 30–40%. Precision poverty alleviation through ecological industries, particularly medicinal plant cultivation and eco-tourism, offers pathways to reconcile economic development with steppe ecosystem preservation. Deployment requires mapping marginal lands for retirement using multi-criteria analysis, establishing water-trading with 20% reduction baselines, and providing transition support, including drought-resistant varieties and guaranteed ecological product purchases.

7. Conclusion

This study provides a comprehensive assessment of ecosystem service values across China's 13 major grain-producing regions from 2008 to 2023, revealing critical insights into the complex relationships between agricultural productivity and ecological sustainability. The spatiotemporal analysis demonstrates that total ESV increased by an average of 68.4% across all regions during the study period, yet this growth masks profound regional disparities and systemic inefficiencies. Provinces with the highest grain output—Heilongjiang, Henan, and Shandong—paradoxically exhibited the lowest per-unit ESV, with values remaining 40–50% below highperforming regions throughout the study period. This production-ecology decoupling indicates that China's grain security has been achieved primarily through extensive land conversion rather than ecological intensification.

The research identifies three distinct regional typologies based on ESV performance and cropland contribution rates. High-ESV regions (Sichuan, Inner Mongolia, Heilongjiang) demonstrated inefficient resource utilization with cropland contributions below 10%, while low-ESV provinces (Henan, Anhui) showed ecological saturation with contribution rates exceeding 20%. The Yangtze River Basin provinces served as models of harmonious development, achieving ecosystem service value growth rates between 6.8% and 7.5% per year alongside moderate production levels. Such results defy normative agricultural development frameworks and highlight the critical need for differentiated strategies that appropriately meet region-specific ecological limits.

The zonation scheme of conservation agriculture, coupled with ecosystem service optimisation, provides a spatially differentiated framework towards sustainable agricultural transformation. If the suggested practices were to be applied, resource savings in the range of 18–22% may be realised in the Huang-Huai-Hai Plain, while water use efficiency could improve by 30–40% in Inner Mongolia. Nevertheless, the enduring regional inequalities during the 15 years of observation indicate that significant refinement change is possible only with restructuring agricultural policy frameworks and governance systems towards embracing holistic ecosystem management as opposed to solely production intensification.

Author Contributions

Conceptualization, B.K. and D.A.A.; methodology, B.K.; formal analysis, B.K.; investigation, B.K.; data curation, B.K.; writing—original draft preparation, B.K.; writing—review and editing, B.K. and D.A.A.; visualization, B.K.; supervision, D.A.A.; project administration, D.A.A. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

This study synthesized data from publicly available sources, including the China Statistical Yearbook, China Grain Network, provincial agricultural databases, and published ecosystem service valuation tables. The compiled and processed datasets are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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